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Influence of Notch Effects Created by Laser Cutting Process on Fatigue Behavior of Metastable Austenitic Stainless Steel

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Abstract

Laser cutting is an attractive and innovative manufacturing process which has many advantages compared to conventional cutting methods. However, with increasing workpiece thickness an increase of the roughness along the kerf surface can be observed, which, in turn, can negatively affect the mechanical properties, in particular the fatigue strength. In this context, the purpose of the present study is to investigate the impact of the geometrical surface characteristics and microstructural changes after laser cutting in order to support the cutting process optimization concerning cyclic durability. Fatigue strength evaluation is performed with specimens cut out by high-power solid-state disk laser from sheets with thickness of 2, 4 and 6 mm made of metastable austenitic stainless steel type 304. Cyclic tests are carried out using a resonant pulsation testing system at test frequencies around 100 Hz at two different load modes, purely reversal load condition (R = -1) and tensile-tensile load condition (R = 0.1). In order to evaluate separately the effect of surface relief over the cutting kerf and burr in form of re-solidified drops, the fatigue specimens are tested at different surface conditions. The investigation comprises fractographic analyses in order to evaluate the influence of the surface roughness and surface-related macro defects on crack initiation. Additionally, phase analyses are performed to assess the deformation-induced phase transformation during cyclic testing and its influence on fatigue behavior, as well as microstructural investigation to analyze the material microstructural changes during the cutting process and its impact on material mechanical properties. The influence on fatigue strength of parts cut by laser is quantified and the characteristic dominating the fatigue life is identified.

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Keywords: laser cutting; notch effect; fatigue behavior; metastable austenitic stainless steel

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1. Introduction

Laser beam cutting can be classified into the group of thermal cutting methods to manufacture plate-shaped materials. This process is distinguished from conventional cutting methods due to the high material utilization rate, high cutting speed, high flexibility and low material deformation at the cutting kerf region. However, with increasing the material thickness an increasing surface roughness along the cutting surface can be observed, which, in turn, can negatively affect the mechanical properties, in particular the fatigue strength [1, 2]. Based on that and on the lack of reliable fatigue strength data from parts cut by laser, the use of this process to manufacture structural thick parts is restricted, limiting the potential application of this process in such cases. Moreover, in order to optimize the cutting process parameters not only concerning the cutting speed and reliability but also to minimize the influence of laser beam cutting on the cyclic strength, the interaction between the process parameters and geometrical and microstructural changes in the region of the cutting kerf and fatigue crack initiation must be identified. It is known, for instance, that a high cutting speed and a low output power produce less pronounced surface relief. Nonetheless, using this process strategy cutting edges with inhomogeneous characteristics are produced [3]. In the case of metastable austenitic steel AISI 304 the use of fiber laser leads to the creation of a high surface roughness for sheets thicker than 4 mm. On the other hand, using CO_2 laser cutting this behavior is just observed for plates thicker than 8 mm [4]. Furthermore, in addition to the laser cutting process, the material composition and the prior surface quality play an important role on the cutting quality, see i.a. [5, 6]. For example, for steel plates with thickness of 25 mm cut by flame cutting it is shown that Cu and Ni in low content levels have a favorable effect on the cutting quality.

The period of fatigue crack initiation phase on the entire fatigue life of samples and components depends not only on the stress level but also substantially on the initial state of the material (defects-afflicted or quasi defect free), the configuration of the defect (macroscopic notch) and, last not least, the surface quality. The assessment of these influencing factors in high cycle fatigue (HCF) and very high cycle fatigue (VHCF) regime must be separated in order to identify the dominant failure relevant effect and thereby to accomplish the basis for the material or strength-oriented process optimization [7]. Due to its good formability the austenitic stainless steels are among the stainless steels the most common used type of material. Moreover, under certain conditions this material can undergo a deformation-induced transformation from austenite to the harder α′-martensite phase [8], which has a beneficial effect on the fatigue resistance [9] and can be used to locally optimize the static and cyclic strength properties of sheet metals by means of the production process [10]. Additionally, to promote the deformation-induced martensite formation, a critical threshold value of plastic-strain amplitude and a certain amount of accumulated plastic strain needs to be exceeded [11].

2. Laser Cutting Process and Experiments

The geometrical surface characteristics of parts cut by laser, to a large extent, depend on the sheet thickness. For this reason, to investigate the influence of laser cutting process on fatigue behavior, specimens of metastable austenitic stainless steel type AISI 304 were cut out by high-power solid-state disk laser from sheets with 2, 4, 6 mm thickness according to the geometries showed in Fig. 1. The cutting machine used is a Trumpf TruDisk 5001 laser source; the most relevant process parameters are listed in Table 1. The parameters from the "laser beam" group normally are related to the cutting machine and cannot be modified. The beam quality M^2 is a parameter which characterizes the deviation of the real beam dispersion from an ideal laser beam with a Gaussian distribution of energy intensity and $M^2 = 1$. To the category "cutting process" belong the parameters focal position and cutting speed which have a strong influence on cutting quality. For this study, it was determined that for the focal position 0 the laser beam is focused on the workpiece top surface.

During the cutting process not only a surface relief is created over the cutting kerf but also burr in form of re-solidified drops are deposited at the cutting edge. In order to separately evaluate these effects the fatigue specimens were tested at three different conditions – laser cutting without post-processing (as-cut condition), trimmed cutting edges (without burr) and electrochemically polished surfaces. The last condition represents the fatigue behavior of the base material. The influence of the plate thickness on the surface quality in the as-cut condition is shown in Fig. 2.

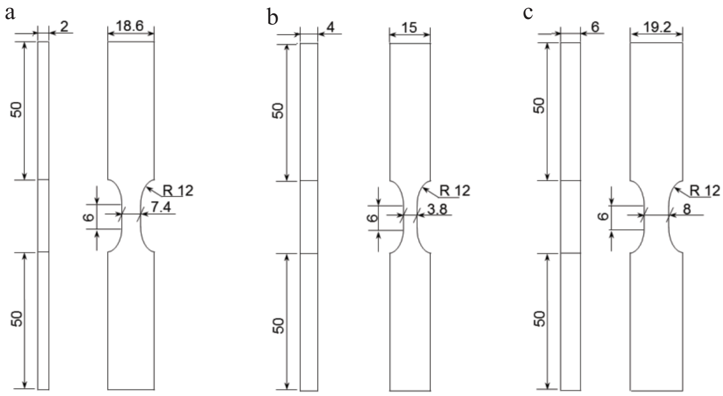


Fig. 1. Geometry of fatigue specimens with (a) 2 mm, (b) 4 mm and (c) 6 mm thickness.

Table 1. Most relevant process parameters used to cut the fatigue specimens.

Group	Plate thickness	2 mm	4 mm	6 mm
Laser beam	wave length [µm]	1.04	1.04	1.04
	beam quality, M^2	10	10	10
	output power [kW]	3	3	3
Shielding / Ejection gas	type of gas	N_2	N_2	N_2
	gas pressure [bar]	11	14	14
	nozzle shape		conical convergent	
	nozzle diameter [mm]	2.3	4	4
	distance nozzle/workpiece [mm]	0.8	0.5	0.5
Cutting process	focal position [mm]	0	-2.6	-2.5
	cutting speed [m/min]	16	5	2.25

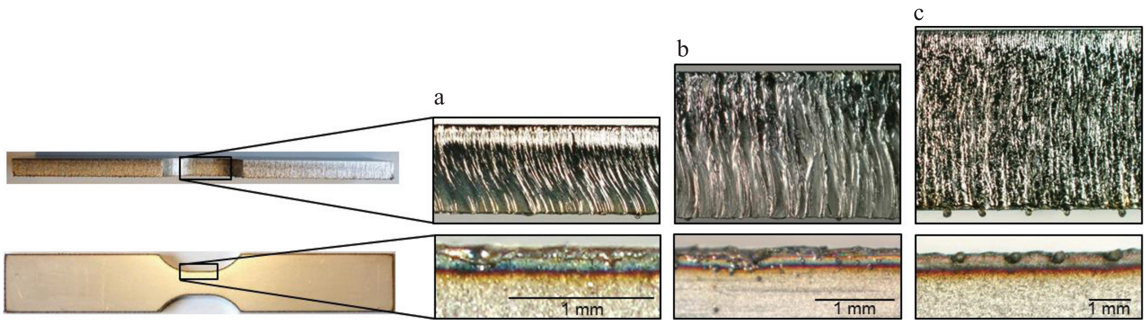


Fig. 2. Surface relief and burr, respectively, after laser cutting of (a) 2 mm, (b) 4 mm and (c) 6 mm sheet thickness.

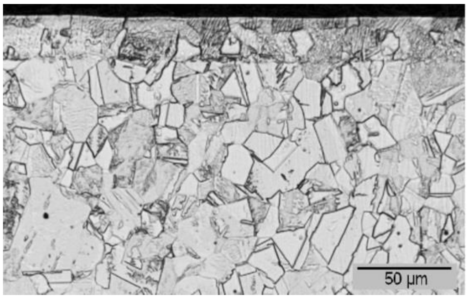
In order to quantify the surface relief characteristics of specimens cut by laser as presented in Fig. 2, roughness measurements were performed by means of a contact profilometer. Table 2 shows the values of the average roughness R_a, average of the difference between the five highest peaks and five deepest valleys R_z and the maximum peak-valley distance R_{max} over the measured length. The measurements were performed at three different positions: at 0.3 mm from the top and bottom edges (position 1 and 3 in Table 2) and at the center line (position 2 in Table 2) for the specimens with three different thicknesses. The results show that increasing the plate thickness, the roughness is more pronounced and it is not constant over the kerf width, becoming rougher from the edge of the laser inlet towards the expelled melted material side (from position 1 towards position 3).

Table 2. Roughness measurements at three different positions for specimens with 2, 4 and 6 mm thickness.

Specimen	Position	R_a [μm]	R_z [μm]	R_{max} [μm]
2 mm thick	1	0.9	6.2	7.3
	2	1.2	8.4	10.7
	3	2.2	14.0	15.0
4 mm thick	1	4.1	20.8	22.9
	2	5.1	29.7	35.8
	3	5.3	32.6	42.4
6 mm thick	1	3.0	18.2	21.6
	2	5.0	27.5	33.3
	3	6.1	35.1	55.7

When the workpiece is being cut by laser beam a portion of the material is melted and expelled by the shielding gas from the cutting kerf. Additionally to the geometric effect, a heat affected zone is created. In Fig. 3a the etched cross section of a sheet with 2 mm thickness in the near-surface area of the laser cutting edge is depicted. One can observe a finer structure from the specimen surface to a depth of approximately 25 μm. It is associated with a hardness increase to 220 HV, which is around 20% higher in comparison to the base material. Moreover, a part of the expelled melted material solidifies on the lower cutting edge regarding the laser beam inlet. It is clear to identify that the geometric inhomogeneity of burr, which is not completely connected to the plate, causes a pronounced macroscopic notch effect introducing a technical crack-like feature; see for this in Fig 3b the cross section of a burr from a sample with 4 mm thickness cut by laser.

a



b

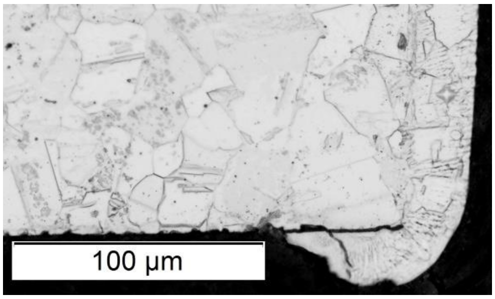


Fig. 3. (a) Microstructure of a sample with 2 mm thickness in the near-surface area of the laser cutting edge; (b) Cross section of a burr from a sample with 4 mm thickness cut by laser.

The fatigue tests were performed in a resonant pulsation testing system from the company Russenberger at load frequencies around 100 Hz. Additionally to the experiments at stress ratio R = 0.1, the samples with 4 mm thickness were also tested at purely reversal loading (R = -1). The samples were cooled during the fatigue tests by compressed air. Temperature measurements at the beginning of the test series showed that no undesired temperature increase occured due to the high test frequency. The decrease of test frequency of $\Delta f > 5$ Hz was applied as a criterion of test interruption. The specimens which did not reach the prescribed test interruption criterion and did not exhibit external crack initiation until the ultimate number of cycles N = 10^7 were evaluated as run-out. The fractographic investigation of the fatigued samples was performed with a scanning electron microscope type JSM 6610 from the company JEOL. Additionally, the phase transformation were assessed by means of electron backscattered diffraction (EBSD) using the microscope Helios Nanolab from the company FEI in conjunction with the EBSD detector from the company EDAX.

3. Results and Discussion

In Fig. 4 the cyclic testing results and respective S-N curves of fatigue samples with different thicknesses in the as-cut condition loaded at R = 0.1 are presented. The horizontal lines in the range around $2x10^6$ and 10^7 load cycles are specified from the fatigue limits determined by stair case tests and statistical analyses [12] with 50% of survival probability and total number of cycles N = 10^7. Without further post-processing, the durability of laser cut components will be influenced by all three effects simultaneously: surface roughness profile, burr at cutting edges and heat-affected zone along the surface. In this case, a tendency towards a decrease of fatigue strength can be observed with increasing sheet thickness.

Fatigue test results for different sample conditions allow the evaluation of the influence of surface roughness and burr at the cutting edges in comparison to the original material represented by electro-chemically polished samples. The test results from specimens with 2 mm thickness without post-processing, with trimmed burr and with electrochemically polished surfaces loaded at R = 0.1 are depicted in Fig. 5a. The fatigue limit analysis according Dixon and Mood [12] for the ultimate number of cycles N = 10^7 and 50% of survival probability shows a fatigue limit of 367 MPa for samples in the as-cut condition. For samples in the polished condition the fatigue limit is 597 MPa. Thus, for the aforementioned conditions, the laser beam cutting of metastable austenitic stainless steel AISI 304 leads to a fatigue strength reduction of around 38%. Comparing the test results of samples with laser cutting kerf in the as-cut condition with the results from specimens where the burr was removed, the improvement of fatigue strength due to the post-processing becomes evident. An increase of the fatigue limit from 367 MPa to 486 MPa can be observed. Thereby an improvement of fatigue strength around 32% arises trimming the burr. A post-processing of the laser cut samples by means of trimming the cutting edges results in a regaining of about 19% in fatigue strength concerning the original material. Hence, the macroscopic notch effect in form of burr seems to have the most detrimental effect on early failure of laser cut samples.

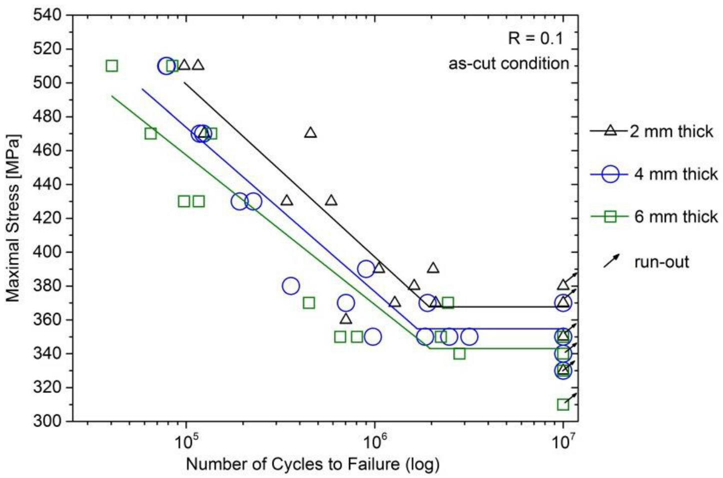


Fig. 4. Fatigue test results and S-N curves of specimens with 2, 4 and 6 mm thickness tested at R = 0.1 in the as-cut condition.

The cyclic testing results for specimens with 4 mm thickness in the as-cut and polished conditions tested at R = -1 are shown in Fig. 5b. It is noticeable that tests carried out under purely reversal loading exhibit high scatter results than tests performed under load ratio R = 0.1. Moreover, a maximum stresses can be reached without failure when the specimens are tested under tensile-tensile than compression-tensile loading condition.

The fatigue limits regarding the maximal stress ($\sigma_{max,D}$) calculated according Dixon and Mood [12] for samples with 2, 4 and 6 mm thickness tested at R = 0.1 und R = -1 for the ultimate number of cycles N = 10^7 and 10%, 50% and 90% of survival probability are listed in Table 3.

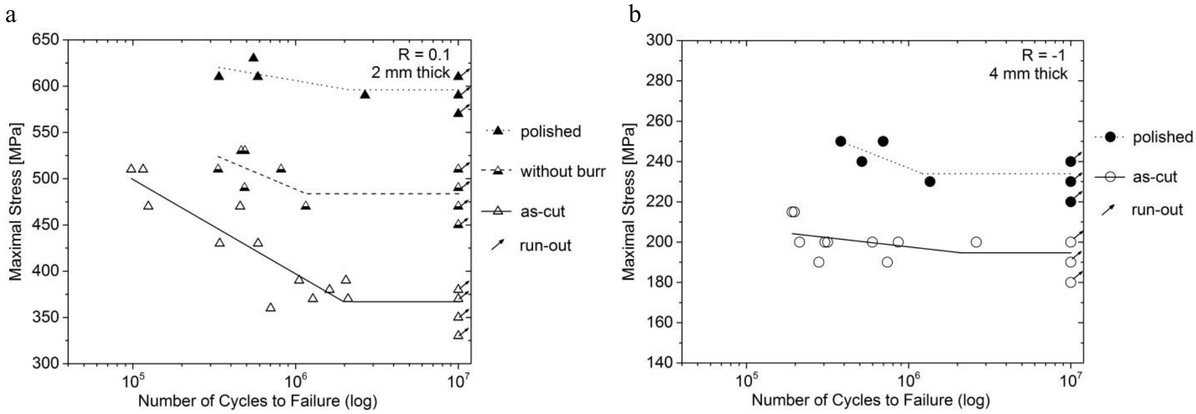


Fig. 5. (a) Fatigue test results and S-N curves of specimens with 2 mm thickness in the as-cut condition, without burr and electrochemically polished tested at R = 0.1; (b) Fatigue test results and S-N curves of specimens with 4 mm thickness in the as-cut condition and electrochemically polished tested at R = -1.

Table 3. Fatigue limits regarding the maximal stress ($\sigma_{max,D}$) for specimens with 2, 4 and 6 mm thickness tested at R = 0.1 and R = -1 with 10%, 50% and 90% of survival probability.

load ratio	R = 0.1	R = 0.1	R = 0.1	R = 0.1	R = 0.1	R = -1	R = -1
thickness	2 mm	2 mm	2 mm	4 mm	6 mm	4 mm	4 mm
condition	as-cut	without burr	polished	as-cut	as-cut	as-cut	polished
$\sigma_{max,D\ 10\%}$, MPa	386	534	615	382	357	209	219
$\sigma_{max,D\ 50\%}$, MPa	367	486	597	353	342	195	233
$\sigma_{max,D\ 90\%}$, MPa	347	437	579	324	328	181	246

A comparison of the fractured surfaces of samples with thickness of 4 mm with and without post-processed burr underlines the previously mentioned assumptions regarding the dominance of the macroscopic notch effect. Crack initiation for samples in the as-cut condition always started at the crack-like notch at the burr, while cracks in samples with trimmed burr normally occurred along the kerf surface, see Fig. 6.

Fig. 7 presents the phase map of a 4 mm thickness sample in the as-cut condition tested at σ_{max} = 380 MPa and R = 0.1 up to failure at 3.56 x10^4 load cycles. In the near-surface area of the laser cutting edge deformation-induced transformation from γ-austenite to α'-martensite can be observed along slip bands and grain boundaries, in the interface between the heat affected zone created by the laser cutting process and the base material and at the laser cutting surface, see Fig. 8a. The formation of martensite along the cutting kerf has a special significance because at the one hand it can counteract the notch effect created by the surface relief based on the creation of a harder surface. On the other hand at the crack tip region, see Fig. 8b, due to the high local plastic deformation in this area, α'-martensite is formed too. With this phase transformation a significant zone of compressive stress in front of the crack tip arises, decreasing the tensile stress field at this region, which, in turn, reduces the crack propagating rate and can cause a crack closure effect [13] due to the volume expansion caused by the phase transformation [14].

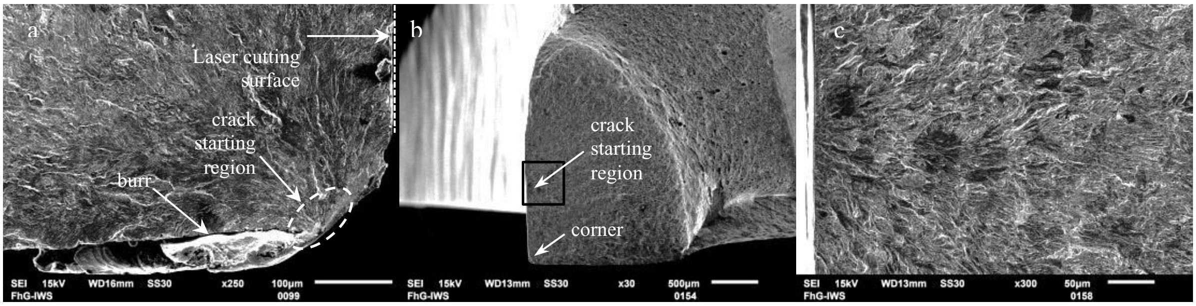


Fig. 6. Fractured surfaces of specimens with 4 mm thickness (a) in the as-cut condition tested at σ_{max} = 200 MPa and R = -1 up to failure at 2.6×10^6 load cycles, (b) without re-solidified drops tested at σ_{max} = 220 MPa and R = -1 up to failure at 4.5×10^5 and (c) more in detail its respective crack starting region.

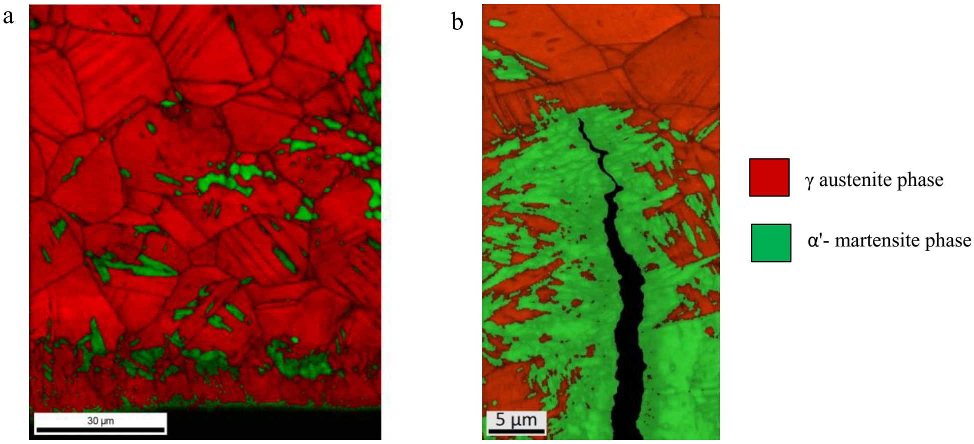


Fig. 7. Phase map of a specimen with 4 mm thickness in the as-cut condition tested at σ_{max} = 380 MPa and R = 0.1 up to failure at 3.56×10^4 load cycles.

4. Conclusions

The influence of laser cutting as a function of plate thickness on the fatigue behavior for a metastable austenitic stainless steel was investigated. It could be shown that increasing the plate thickness a pronounced surface relief of the cutting surface is formed, consequently decreasing the fatigue strength. A significant reduction could be attributed to the notch effect of the re-melted drops on the cutting surface edge. Depending on the dominance of the respective notch effect the crack initiation can occur either on the cutting edge, or in the center region of the cutting area. Nevertheless, it makes little sense in a manufacturing process with high cutting speed and high efficiency as laser cutting to add a surface post-processing. However, an adjustment of the process parameters can already make headway in avoiding or minimizing the formation of burr with the process optimization, offering the likely perspective of a significant increase in fatigue strength. The study identified the microstructural changes caused by laser cutting process and the regions where phase-transformation induced by deformation take place. Future work must clarify in which extend the fatigue strength is influenced by these factors.

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